Coaxial Multiplexer for Time Domain Reflectometry Measurement of Soil Water Content and Bulk Electrical Conductivity

ABSTRACT

Time domain reflectometry (TDR) is increasingly used for measurement of soil water content and bulk electrical conductivity in agricultural, hydrological, environmental and infrastructure research and development. The TDR technique uses reflections (wave forms), from a probe buried in the soil, of a fast rise time voltage step. The advent of automatic systems for collecting many TDR wave forms has brought the need for a multiplexer to connect the probes to a TDR instrument without introducing distortion of the wave form. A 16-channel (1P16T), 50 Ω coaxial multiplexer was developed to switch the TDR signal. Control is by synchronous serial addressing using three lines capable of producing TTL level signals similar to those from the parallel port of a personal computer. The multiplexer has 16 jumper selectable addresses. Testing on five multiplexers showed that quiescent power consumption was 6 mA at 12 VDC, peak power consumption was 101 mA, and average power consumption during switching was 54 mA. Wave form placement on a cable tester screen was not affected by the multiplexer channel used. The standard deviation (SD) of horizontal placement was 0.012 ns which compares favorably to the 15.6 ns full screen width of the wave form (five multiplexers by 16 channels each = 80 measurements; 30 cm probe length). Multiplexer channel also had negligible effect on computed travel times of the TDR pulse in a water content probe. The SD of 0.011 ns for a mean travel time of 8.68 ns was only slightly larger than the SD of 0.007 ns obtained when 80 wave forms were captured using the first channel of one multiplexer. Corresponding SD values for water content were 0.0006 and 0.0004 $m^3\ m^{-3}$, respectively. The multiplexer used and the multiplexer channel had no important effect on the wave form voltage levels needed for determination of bulk electrical conductivity (BEC). The ratio of final voltage to incident voltage, which is directly proportional to conductivity, had a SD of 0.0002 when measured 80 times on channel one of one multiplexer and a SD of 0.0006 when measured once on each of the 16 channels of five multiplexers. Compared with a TDR probe connected directly to the cable tester, adding one multiplexer in series caused no change in travel time or water content, while adding two multiplexers in series caused a change in water content of 0.003 $m^3\ m^{-3}$. As each multiplexer was added to the system the voltage ratio increased by 2 % in a reproducible and expected way that can be included in system calibration for BEC measurements. The multiplexer developed is reliable and accurate for measurements of soil volumetric water content and bulk electrical conductivity.

Keywords: TDR, time domain reflectometry, multiplexer, soil water content, bulk electrical conductivity, soil salinity.

INTRODUCTION

Time domain reflectometry lends itself to automated monitoring of soil water content (Baker and Allmaras, 1990; Heimovaara and Bouten, 1990; Evett, 1994) with numbers of soil probes rising to the several tens or even hundreds in a single measurement system. The most basic TDR system consists of a pulse generator, providing a step increase in voltage with a very fast rise time (typically 150 picoseconds), and a fast oscilloscope that captures the wave form reflected from an attached cable or other waveguide (Topp et al., 1980). For water content measurement a special wave guide usually called a soil probe is buried in the soil. A TDR cable tester such as the Tektronix[1] 1502 provides the pulse generator and oscilloscope in a tightly integrated unit with 50 Ω output impedance. The cable tester may be adjusted to display on its screen any portion of the wave form including that part showing reflections from the probe. Multiplexers for switching the TDR wave form between probes have either been expensive (e.g., the relay scanners used by Thomsen and Thomsen, 1994), have a limited number of channels (e.g., six, Heimovarra and Bouten, 1990; eight, Campbell Scientific Inc. model SDMX50, Logan, Utah; eight, JFW Industries, Inc. model 50S-608 BNC, Indianapolis, Indiana), or were not capable of providing a 50 Ω wave guide suitable for switching coaxial cable with minimal loss of wave form information (e.g., the rotary wafer switches used by Baker and Allmaras, 1990; and Herkelrath et al., 1991). Some multiplexers cannot be switched directly between any two channels but must be switched in a predetermined order, thus reducing flexibility. This paper discusses the design, and laboratory and field testing of a 16-channel coaxial multiplexer.

DESIGN GUIDELINES

Guidelines for design of a multiplexer may be generated by examination of the TDR water content measurement system. Consider a trifilar TDR probe consisting of three stainless steel rods buried parallel to one another in a moist sand (non-saline) with the proximal ends connected to coaxial cable (Fig. 1). The soldered connections are potted in epoxy forming the probe handle. The perpendicular distance between the rods is the separation distance, s, and the exposed length is L. Typically the coaxial cable would have a characteristic impedance of 50 Ω. In this cartoon the wave form shows the reflections caused by the various parts of such a probe (Fig. 1). In particular, we are interested in the one way travel time, tt, necessary for the pulse to travel along L, the exposed length of the stainless steel rods. Note that although the cable tester gives distance as the units of the horizontal axis it really measures time. In an automated system the wave form is interpreted by computer analysis of features such as those described in Fig. 2. The overall width of the wave form in Fig. 2 is about 9 nanoseconds (ns) for a 20 cm probe length; and tt = t2 - t1 is about 6 ns. The width of the smallest features, such as the peak at t1, is of the order of a fraction of a nanosecond. Computer algorithms for graphical wave form interpretation usually focus on finding peaks in the first derivative and fitting tangent lines to features of the wave form such as the first and second rising limbs and first descending limb (e.g., Baker and Allmaras, 1990; Heimovaara and Bouten, 1990). A tangent is often fit to the base line between t1 and t2 as well. Any change in the rise time of the TDR pulse will affect the slopes of these features and thus may affect the measured travel time. For good reproducibility, measured travel times should not vary by more than 0.01 of tt from channel to channel or among multiplexers.

[1]The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation or exclusion by the USDA-Agricultural Research Service.

Clearly a multiplexer for connecting probes to a cable tester must cause minimal distortion of the wave form if graphical interpretation is to succeed. This is especially true because other characteristics of the TDR system or soil may remove information from the wave form. For instance, the bulk electrical conductivity (BEC) of the soil increases with salinity and may increase with clay content and water content for certain clay types. As the BEC of the soil increases, the impedance of the wave guide in the soil decreases due to the lowering of the resistance component of impedance. In addition, there is a lowering of signal voltage along the length of the rods due to conduction through the soil. This causes the wave form level after the first peak to decline relative to that for a soil of lower BEC. It also lowers the slope of the second rising limb (Dalton and Van Genuchten, 1986; Topp et al., 1982; Hook and Livingston, 1995); and the final height to which the wave form rises after the second inflection. This latter fact has been used successfully to find the BEC of soils (e.g., Dalton et al., 1984; Topp et al., 1988; Wraith et al., 1993). Topp et al. (1988) and Spaans and Baker (1993) determined that the most accurate method of determining the bulk electrical conductivity (BEC) is the Giese-Tiemann approach.

$$BEC \ = \frac{1}{120\pi L}\frac{Z_0}{Z_u}\left[\frac{2(V_0-V_i)}{V_f-V_i}-1\right] \qquad\qquad [1]$$

where Z_0 is the characteristic impedance of the probe, Z_u is the output impedance of the cable tester (50 Ω), V_i is the voltage in the cable tester before the pulse is injected (i.e. virtual ground), V_0 is the voltage of the incident pulse before the probe, and V_f is the voltage at great distance from the cable tester after all multiple reflections have been included in the wave form. Obviously, for measurement of BEC, it is important that wave form voltage level not differ between wave forms acquired on different channels of multiplexers or on different multiplexers.

The lowering of the slope of the second rising limb is due to attenuation of high frequency components of the signal and can increase the difficulty of finding t2. Cable length can also influence the amount of information in the wave form. As the pulse moves down the cable to the probe its higher frequency components are selectively attenuated. In effect, the cable acts as a low pass filter. This means that the longer the cable, the slower the rise time of the pulse at the probe. The slower rise time causes the rising and descending limbs of the inflections caused by probe handle and end of rods to be less steep. That is, transition time increases (Hook et al., 1992; Hook and Livingston, 1995). Thus the measured travel time, tt, may be affected by cable length (Heimovaara, 1993). Moreover, if the probe is short enough, the descending limb of the first peak will intersect the rising limb of the second inflection, causing the travel time to be incorrect. The longer the cable, the lower the slope of the descending limb and the longer the probe must be to avoid this problem. Because the slope of the descending limb also decreases with increasing BEC of the soil (see Dalton and Van Genuchten, 1986, Fig. 3), a probe length adequate for a given cable length is difficult to predict. Another problem associated with long cable lengths is the loss of the first peak altogether. A multiplexer design should guarantee that high frequency components of the wave form are attenuated as little as possible in the multiplexer.

Due to series resistance in the cable, cable length also affects the voltage levels measured for BEC; resulting in sometimes important errors (Heimovaara et al., 1995; Mallants et al., 1996). Adding connectors increases the series resistance as well; and in larger measure than equivalent lengths of cable. The multiplexer design should minimize circuit board trace length to minimize series resistance losses.

Although proprietary systems exist for TDR measurement of soil water content, perhaps the most common TDR instrument for this purpose is the Tektronix 1502B/C series TDR cable testers. In various systems, this instrument has been controlled and wave form data transferred for storage using the RS-232 serial port of an IBM PC compatible computer (Evett, 1994) or a serial connection to a data logger. In field applications, small size and low weight are desirable computer characteristics, so portable computers are usually chosen. Commonly these have only a single serial port and parallel port and, because the serial port is used to communicate with the cable tester, we must use some of the eight output pins of the parallel port to control the multiplexer. Control using the parallel port could be accomplished with either a parallel or a serial digital signal. The serial signal is preferred because it uses fewer parallel port pins. For example, the computer could send a synchronous serial signal of virtually any desired length using only three pins: one for clocking, one for data, and one for serial device enabling. Because it is difficult to control the timing of parallel port output, a synchronous signal using clock and data lines is preferable over an asynchronous serial signal. The synchronous clocking eliminates the need for precise timing and reduces the complexity of the multiplexer circuitry. With a serial signal, the number of distinct addresses can be practically unlimited. By contrast, the number of addresses is limited to 256 using a parallel signaling scheme. If we use 4 pins for the multiplexer address and 4 pins for the input address we can have just 16 multiplexer addresses and 16 inputs on each multiplexer. Also, with a parallel scheme we have no pins left over for other uses. Other uses would include controlling power to the cable tester (to reduce power consumption in solar powered systems), and toggling the older model Tektronix 1502 cable tester to output a wave form. Many data loggers also support some sort of digital control using TTL level signals. Commonly, these loggers have fewer than eight output lines making the need for a serial addressing scheme even more apparent.

The Tektronix models 1502B and 1502C allow digital control of wave form position on the screen. This allows cable lengths to different probes to differ because software can be written to control the cable tester to correctly position the wave forms from different probes as the multiplexer switches from one probe to another. However, the older model 1502 cable tester, still in wide use, can only be controlled manually. In a system using the model 1502, the wave guide lengths to all probes must be identical so that the cable tester can be adjusted once to position the wave form and the system left unattended thereafter. Thus a multiplexer design must have equal circuit board trace lengths to all coaxial cable connections.

Some multiplexers allow switching only in a pre-determined order, from channel 1 to 2 to 3, etc. This reduces flexibility for the user who may wish to read a probe on channel 8 first, then channel 3, etc. Another requirement for field use is low power consumption. From a manufacturing and repair perspective, the multiplexer should be easy to build, use common components, and be modular in design for easy replacement of circuit boards and so that some circuitry may be used for other products.

The objective was to design a TDR multiplexer to meet the following guidelines; and to test multiplexer power consumption and wave form reproducibility for all channels and for multiple multiplexers:

1) Addressability so multiple multiplexers may be controlled using the same wires.
2) Synchronous serial addressability so the low cost and common parallel port can be used, so the minimum number of output lines can be used, and so multiplexer circuitry may remain simple.
3) Compatibility with TTL level control signals available on the parallel port.
4) Low power consumption.
5) BNC connectors for coaxial cabling to match those commonly used in TDR work.

6)   Wave guide impedance close to 50 Ω throughout the multiplexer to minimize loss of high frequency signal components.
7)   Compact circuit board layout to minimize trace lengths and series resistance losses.
8)   Modular design for ease of repair and multiple use of circuitry.
9)   Equal trace lengths to all connectors.
10)   No channel or multiplexer specific effects on travel times or wave form voltage levels.
11)   One step switching between any two channels regardless of order.

DESIGN

        The design used two circuit boards of equal size connected to each other by single in-line pin headers and sockets. The control circuitry was implemented on one board called the control board and the BNC connectors, relays, and power and control connector were placed on another board called the relay board. Coaxial cable connectors were BNC female type because these fit the most common connector used with TDR soil probes. The two-board design provided three advantages. First, the control circuitry is the most susceptible to damage from, for instance, a nearby lightning strike and having the control board separate allows quick replacement, in some cases without even disconnecting the TDR soil probes from the relay board. Second, the control circuitry is somewhat generic and the same board can be used to control other types of multiplexers such as those for multiplexing low level DC sensor signals. Third, having the control circuitry on another board allows the ground plane on the relay board to be as complete as possible, increasing TDR signal integrity. Both circuit boards were 1.6 mm (1/16 inch) FRP with 28 g (1 oz) copper facing on both sides. Holes were plated through and a solder re-flow was applied to the boards after etching.
        A tree structure provides the simplest and probably most efficient way to provide equal trace lengths on a circuit board. This may be implemented with seven relays to provide eight connections to a single input from the cable tester; but mirroring this pattern provides 16 BNC connections, each through some combination of 15 relays, to a single, central BNC connector on the relay board (Fig. 3). Omron G5Y-1 12 VDC, 50 Ω RF relays were used to match wave guide impedance. Their small size allowed for a compact circuit board. Manufacturer listed characteristics are isolation of 70 to 60 dB minimum, insertion loss of 0.5 dB maximum, and VSWR of 1.5 to 1.8 maximum over a frequency range of 250 to 900 MHz for a 50 Ω impedance circuit. The relays have a normally closed side and a normally open side in a single-pole double-throw configuration with ground pins on either side of signal pins. Relays, BNC sockets and the five pin polarized connector socket for power and control signals were mounted on the top of the board that was also the top of the completed multiplexer (Fig. 4). Plated through holes allowed the ground legs of the BNC sockets to be electrically connected with the ground plane on the top side of the board. For connection to the control board, single in-line header sockets were placed at opposite ends of the relay board on the solder (back) side. Plated through holes allowed connection of the headers to both sides of the PCB. All traces to relay coils as well as TDR signal traces were placed on the solder side of the relay board (Fig. 3) leaving almost the entire top side of the relay board for the TDR signal ground plane. The TDR signal ground plane was electrically separated from the switching signal ground.
        The control board employs CMOS logic and driver ICs to minimize quiescent current and susceptibility to noise (Fig. 5). Synchronous serial communication is accomplished with three lines, data, clock, and serial enable; switched at TTL levels. Communication starts when the enable line is set high, after which the clock line is set high and then low eight times. Each time the clock line is high the data line is set either high or low to signal either a 1 or 0. Each time the clock line goes low the signal

on the data line is registered by an eight bit serial to parallel shift register (74HCT164 IC). After the eight data bits are registered, the data and clock lines are set low followed by the enable line. The first four bits of data define one of 16 addresses to which the multiplexer may be set by moving a jumper. The second four bits define one of 16 coaxial I/O locations on the relay board. The four lines for the multiplexer address are connected to the four inputs of a latching 4 to 16 line decoder (4514 IC) shown as 4514#1 in Fig. 5. The 16 outputs of 4514#1 are individually connected to the inner side of 2 banks of 8 double row pin headers placed on opposite sides of the 4514. The outer side of each row is interconnected and feeds into both sides of one gate of a quad 2-input NOR gate (4001 IC). Placement of a single jumper connecting the inner and outer sides of either header sets the address for that multiplexer.

The four lines from the CD74HCT164 defining the coaxial input location go to another 4514 IC shown as 4514#2 in Fig. 5. The inhibit and strobe pins of 4514#2 are tied together and connected to the output of a quad 2-input NAND Schmitt trigger (4093 IC) wired as a negative edge detector. When the multiplexer address is correct, the output of 4514#1 passes through the address select jumper and feeds into both sides of gate 2 of the 4001 giving a logic 0 output (low). The high signal from SDE is combined with this low in gate 1 of the 4001 giving a low output that is fed into both sides of gate 4 producing a high output. The output of gate 4 is connected to the input of the Schmitt trigger (gate 4 of the 4093). Note that the output of gate 4 is always high unless both SDE is low and gate 2 output is low (correct multiplexer address, see Table 1). When SDE goes low at the end of signaling, the resulting negative going edge on the input of the Schmitt trigger causes a brief positive voltage pulse output that is seen on the inhibit and strobe pins of 4514#2, causing the four bit address to be latched, thus setting the corresponding output pin of 4514#2 high. The 16 outputs of 4514#2 are connected to the input sides of two peripheral drivers (ULN2003 and ULN2803) via a network of switching diodes (1N914). The diode network defines logic such that the relays come on as needed to pass the TDR signal through the multiplexer (Fig. 5). The peripheral drivers act as sinks when driven by the signals from the diode network. Each relay coil is connected to 12 VDC on one side and to a peripheral driver pin on the other. The multiplexer may be switched directly to any of the 16 input channels. Total component cost, including circuit boards, was USD 170.00 in 1995. A short BASIC program for controlling the multiplexer from the computer's parallel port is available as TR200TST.EXE (BAS, INI) on the Internet (see http://www.cprl.ars.usda.gov/programs/index.html).

TESTS

Testing addressed issues of power consumption, and of wave form reproducibility for all input locations and for different multiplexers. A computer program (TACQ.EXE) was written to control up to 16 multiplexers using three pins of an IBM PC compatible parallel port (available for download at http://www.cprl.ars.usda.gov/programs/). The program also controlled a Tektronix model 1502C cable tester (150 ps rise time) and captured wave forms from the cable tester via the computer's serial port. The program automatically interpreted the wave forms to find the travel time of the voltage step through the TDR probe; and found the voltages needed for BEC calculation. Five multiplexers were tested for power consumption. Power was supplied at 12 VDC and current was measured with each multiplexer switched to each of the 16 input locations.

Wave form reproducibility was tested using the five multiplexers and a single TDR probe placed in sand saturated with distilled water. A wave form was captured for each input location of each multiplexer by connecting the TDR probe to each input and switching the multiplexer to that input before capturing the wave form. This provided 80 wave forms. For comparison, another 80 wave

forms were captured using channel one of one multiplexer. Wave forms were compared by using the computer program to interpret the wave forms and comparing the measured travel times, dielectric constants, water contents, and relative voltage levels. Wave form interpretation algorithms used were those embedded as defaults in the TACQ program. Water contents were calculated using Topp's Eq. 7 (Topp et al., 1980). The probe used was a trifilar design with 30-mm rod-to-rod spacing, 3.2-mm rod diameter, 300-mm exposed rod length, and an epoxy and acrylic plastic handle encapsulating the connection between the rods and the 50-Ω coaxial cable (available as model TR-100/30cm from Dynamax, Inc., Houston, TX).

  We measured the three relative voltage levels used in Eq. 1 - the initial voltage in the cable tester, V_i, the pre-incident voltage step just before the probe (base line before 1st peak in Fig. 2), V_0, and the final voltage of the wave form (in our case at 599 m), V_f. The value of V_i is virtual ground or zero and the relative values of the other voltages are obtained by subtracting V_i from their measured values. The BEC method of Dalton et al. (1984) uses the relative voltage of the "global minimum", V_{min}, identified in Fig. 2, so it was measured as well. The value of V_{min} was, of course, a single value. The value of V_0 was obtained by moving the wave form view to the left one tenth of the width of the view shown in Fig. 1 and taking the mean of the first 25 data. This avoided inclusion of any data from the first peak in the value of V_0. To acquire V_f, the distance per division was changed to 1 m, the wave form was set to begin at 599 m, and the mean value of the last 50 data points was taken. To acquire V_i, the start of the wave form was set to -0.51 m (before the step pulse is injected into the signal), the distance per division was set to 0.1 m, and the mean of the first 25 data points was taken. A final value that was acquired was the voltage of the step pulse in the cable connected to the cable tester, V_r, which was used by Baker et al. (1996) in measurements of CO_2 levels in air using TDR and a coaxial conductivity cell. This value was obtained from the same wave form as for V_i, but was the mean of the last 25 data. Cabling was 50 Ω RG58/AU coaxial cable with BNC clamp type connectors. The cable from the cable tester to the multiplexer was 3 m long, as was the cable from the multiplexer to the probe.

  To evaluate the effect of including one or two multiplexers in the circuit path we later performed a second series of tests using a 20 cm trifilar probe of the same design (available as model TR-100/20cm from Dynamax, Inc., Houston, TX) with 3 m of cable, again embedded in sand saturated with distilled water. Three sets of 80 measurements were made. For the first set the probe was connected to a secondary multiplexer that was in turn connected to a primary multiplexer via a 0.92 m extension cable; the primary multiplexer being itself connected to the cable tester with a 3 m extension cable. This is the most common connection topology for large multiplexed systems. The combined extension cable length was 3.92 m. In order to minimize changes in voltage level caused by series resistance, and changes in transition time caused by filtering of high frequency components; this combined length was retained for the second and third measurement sets. For the second set of measurements the probe was connected to a primary multiplexer that was connected in turn to the 0.92 m and 3 m cables spliced together and connected to the cable tester. For the third measurement set the probe was connected to the spliced 0.92 m and 3 m cables, which were connected to the cable tester. The splices were made using standard 50 Ω female to female connectors, which increased the cable length by 1.5 cm each.

  The G5Y-1 relay is rated for a minimum of 300,000 operations at an operating frequency of 1,800 operations per hour. The typical TDR system operates much more slowly with times between measurements of 15 min or greater so we could expect the life of the multiplexer to exceed 8.5 years. Although formal field testing was not done for this paper, a report of sustained field use will be made in the Results and Discussion. These multiplexers may be connected in any configuration; but the most efficient configuration is provided by connecting up to 16 secondary multiplexers to one primary

multiplexer. In this configuration a coaxial cable connects the TDR cable tester to the center connector of the primary multiplexer. Each of the other 16 multiplexers is connected by a coaxial cable connected to its central BNC connector and to one of the BNC connectors on the edges of the primary multiplexer. Up to 256 probes may be connected to the secondary multiplexers. Two of the secondary multiplexers share an address, but this causes no problem because only the desired multiplexer is connected to the cable tester through the primary multiplexer at any time.

RESULTS AND DISCUSSION

When switched to input no. 1 (no relays powered) the multiplexer used 6 mA at 12 VDC (Table 2). The maximum number of relays are powered when the multiplexer is switched to channel no. 16, resulting in the maximum power consumption for one multiplexer of 102 mA at 12 VDC. The minor differences in current used by different multiplexers switched to the same channel can be attributed to the normal range of component current draw. Up to 17 multiplexers may be used in one system; but most of the time only two multiplexers need be switched at any one time when connected as described in the previous section. In this case, the maximum current necessary is 288 mA at 12 VDC (two multiplexers drawing 102 mA each and 14 multiplexers drawing 6 mA each). In a 17 multiplexer system, if the two secondary multiplexers that share an address were being switched, the maximum current necessary would be 390 mA. (We used the high sensitivity version of the G5Y-1 relay, the G5Y-1-H, to build one multiplexer that used a maximum of 73 mA. A 16 multiplexer system using this relay would consume 230 mA maximum.) To minimize power consumption, the software was written to switch any multiplexer not in use to channel no. 1.

In field practice the multiplexers are off almost all the time so power consumption is not too great. For example, a field measurement system at Watkinsville, Georgia, employed five multiplexers, 60 probes at various depths to 150 cm, a Tektronix model 1502B cable tester, and a notebook computer (Radcliffe et al., 1995). Taking measurements every 15 minutes, it operated continuously year-round from two 55-W solar panels charging a bank of 12 VDC deep-cycle lead-acid marine batteries. In this system, the notebook computer had power management enabled so that between measurement cycles the hard disk, LCD screen backlight, and other peripherals were turned off. Also, the program turned off the power to the cable tester between measurement cycles. During long cloudy periods in the winter, this system required re-charging of the batteries about every two weeks.

The channel to which the multiplexer was switched had negligible effect on the wave form as evidenced by little variation in travel times, volumetric water contents (θ_v), and apparent dielectric constants (Table 3) for 80 wave forms measured by switching each of five multiplexers to each channel and acquiring a wave form. The θ_v varied by an maximum value of only 0.003 m^3 m^{-3} over the 80 readings with a corresponding variation of only 0.046 ns in travel time. The SD of θ_v was much lower, at 0.0006 m^3 m^{-3}, which is considerably better than the best SD value of 0.004 m^3 m^{-3} reported by Baker and Allmaras (1990); the SD of 0.005 m^3 m^{-3} reported for a sandy soil by Heimovaara and Bouten (1990); or the SD of 0.003 m^3 m^{-3} reported by Herkelrath et al. (1991); for their respective multiplexed systems in outdoor settings. By comparison, when 80 wave forms were acquired through channel one of a single multiplexer the maximum variation of θ_v was 0.002 m^3 m^{-3} with a SD of 0.0004 m^3 m^{-3}, and the maximum variation of travel time was 0.038 ns. Thus the variation due to switching among channels was barely larger than the variation due to random noise on a single channel. The position of the wave form on the screen changed very little with channel, the maximum variation of t1 being only 0.068 ns. By comparison, the maximum variation of t1 for the 80 readings on channel 1 of a single multiplexer was 0.030 ns. Compared to the full-screen apparent width of 15.6 ns, these are both

very small variations.

The final voltage level, V_f, was very reproducible from one multiplexer to the next and one channel to the next (Table 4). The variation due to different channels and multiplexers was only slightly larger (SD = 0.24) than the variation for repeated readings (80) on channel one of one multiplexer (SD = 0.15). Variation due to switching channels and multiplexers was also low for V_i and V_r. The variability of V_0, although doubled when switching between channels and multiplexers, was still low. The value of V_{min} was more variable than the other voltages measured and was not much increased by switching between channels and multiplexers. The value of the quantity $[(2V_0/V_f) - 1]$, used in calculation of BEC, averaged 0.1296 for 80 samples on channel one of one multiplexer with SD of 0.0002 and averaged 0.1295 for the 80 samples from all 16 channels of the five multiplexers with SD of 0.0006. Although the multiplexer introduces some variability in the voltages measured, this added variability is small. For example, the coefficient of variation, CV, for the 80 samples from all 16 channels of the five multiplexers was 0.0046, which is somewhat smaller than the CV of 0.0064 reported by Wraith et al. (1993) for 70 measurements of electrical conductivity in a silt loam soil column with constant water content and unchanging electrical conductivity.

Compared with values measured with no multiplexer in the circuit, values of V_i, V_r, and V_f were essentially unchanged by using one or two multiplexers (Table 5); and values of the changes, when they occurred, were only slightly larger than the value of SD. The values of V_0 and V_{min} were changed more; with V_0 increasing by 2.7, and V_{min} increasing by 4.1, as two multiplexers were added. Such change was expected because the multiplexers increase the signal path length by about 0.19 m each (measured with propagation velocity factor set to 0.64), thus increasing the series resistance (impedance). Values of the quantity $[(2V_0/V_f) - 1]$ increased by 2 % each time a multiplexer was added; with the increase related mostly to the expected increase in value of V_0 as multiplexers were added. Heimovaara et al. (1995) and Mallants et al. (1996) showed how to include this impedance increase, caused by additional signal path length and connecters, in the calculation of BEC.

Values of travel time for t1.bis, t1, and t2 should not be directly compared for zero, one, and two multiplexers in the system because the addition of each multiplexer required that the wave form be repositioned on the cable tester screen, causing small variations in the position of t1.bis, t1, and t2. The SD of t1.bis and t1 changed only slightly as 1 and then 2 multiplexers were added, and SD for t2 changed not at all (Table 5). The SD for the travel time, tt, did not change appreciably. The value of tt and water content did not change appreciably when one multiplexer was added to the circuit, but increased by 0.6 % when a second multiplexer was added. The change in water content of 0.003 $m^3\ m^{-3}$ is small compared with the precision of calibration equations reported in the literature.

In 1994, six multiplexers were used at a field site near Lubbock, Texas, to measure soil water content in a cotton field with 85 probes placed at depths of 0.05, 0.10, 0.20, and 0.30 m (Lascano et al., 1996). In 1995 and 1996, an additional multiplexer was added to the TDR system and 90 probes were measured using a tree configuration of the multiplexers (six multiplexers with probes attached were each connected to the seventh). Each of the three years, the TDR system was operated for five months starting in June. The computer was housed 100 m from the cable tester and somewhat farther from the multiplexers, showing that reliable communications with the cable tester and multiplexers could be achieved with rather long cables.

In summary, the multiplexer performed as designed and delivered wave forms that revealed no important differences when different multiplexer channels or different multiplexers were used. The multiplexer performs well for both automatic water content as well as automatic bulk electrical conductivity measurements. Variabilities of travel times, of water contents, and of the voltage ratio that is proportional to electrical conductivity were all lower than comparable values reported in the literature. When wave forms were compared for zero, one, and two multiplexers in the system there

was little change in voltage levels and only a 2% change in the quantity $[(2V_0/V_f) - 1]$. Water contents did not increase when one multiplexer was added to the system, but increased by 0.003 m^3 m^{-3} when two multiplexers were used in series.

REFERENCES

Baker, J.M., and Allmaras, R.R. (1990) System for automating and multiplexing soil moisture measurement by time-domain reflectometry. Soil. Sci. Soc. Am. J. 54(1):1-6.

Baker, J.M., Spaans, E.J.A., and Reece, C.F. (1996) Conductimetric measurement of CO_2 concentration: Theoretical basis and its verification. Agron. J. 88(4):675-682.

Dalton, F.N., Herkelrath, W.N., Rawlins, D.S., and Rhoades, J.D. (1984) Time-domain reflectometry: simultaneous measurement of soil water content and electrical conductivity with a single probe. Science 224: 989-990.

Dalton, F.N., and van Genuchten, M. Th. (1986) The time-domain reflectometry method for measuring soil water content and salinity. Geoderma 38:237-250.

Evett, S.R. (1994) TDR-Temperature arrays for analysis of field soil thermal properties. In Proceedings of the Symposium on Time Domain Reflectometry in Environmental, Infrastructure and Mining Applications, Sept. 7-9, 1994. Northwestern University, Evanston, Illinois. U.S. Dept. of Interior, Bureau of Mines, Special Publication SP 19-94.

Heimovaara, T.J. 1993. Design of triple-wire time domain reflectometry probes in practice and theory. Soil Sci. Soc. Am. J. 57(6):1410-1417.

Heimovaara, T.J., and Bouten, W. (1990) A computer-controlled 36-channel time domain reflectometry system for monitoring soil water contents. Water Resour. Res. 26(10):2311-2316.

Hiemovaara, T.J., A.G. Focke, W. Bouten, and J.M. Verstraten. 1995. Assessing temporal variations in soil water composition with time domain reflectometry. Soil Sci. Soc. Am. J. 59(3):689-698.

Herkelrath, W.N., Hamburg, S.P., and Murphy, F. (1991) Automatic, real-time monitoring of soil moisture in a remote field area with time domain reflectometry. Water Resour. Res. 27(5):857-864.

Hook, W.R., Livingston, N.J., Sun, Z.J., and Hook, P.B. (1992) Remote diode shorting improves measurement of soil water by time domain reflectometery. Soil Sci. Soc. Am. J. 56(5):1384-1391.

Hook, W.R., and Livingston, N.J. (1995) Propogation velocity errors in time domain reflectometry measurements of soil water. Soil Sci. Soc. Am. J. 59(1):92-96.

Lascano, R.J., Baumhardt, R.L., Hicks, S.K., Evett, S.R., and Heilman, J.L. (1996) Daily measurement and calculation of crop water use. *In* C.R. Camp, E.J. Sadler, and R.E. Yoder (Editors) Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling. Nov. 3-6, 1996, San Antonio, Texas, U.S.A.

Mallants, D., M. Vanclooster, N. Toride, J. Vanderborght, M. Th. Van Genuchten, and J. Feyen. 1996. Comparison of three methods to calibrate TDR for monitoring solute movement in undisturbed soil. Soil Sci. Soc. Am. J. 60(3):747-754.

Radcliffe, D.E., Steiner, J.L., Ter Haar, M., and Visser, P. (1995) Monitoring infiltration and redistribution using time domain reflectometry. p. 193. *In* Agronomy abstracts. ASA, Madison, WI.

Spaans, E.J.A., and Baker, J.M. (1993) Simple baluns in parallel probes for time domain reflectometry. Soil Sci. Soc. Am. J. 57(3):668-673.

Thomsen, A., and Thomsen, H. (1994) Automated TDR measurements: Control box for Tektronix TSS 45 relay scanners. SP Report No. 10, 1994. Ministry of Agriculture, Danish Institute of Plant and Soil Science. Denmark

Topp, G.C., Davis, J.L., and Annan, A.P. (1980) Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour. Res. 16(3):574-582.

Topp, G.C., Davis, J.L., and Annan, A.P. (1982) Electromagnetic determination of soil water content using TDR: I. applications to wetting fronts and steep gradients. Soil Sci. Soc. Am. J. 46(4):672-678.

Topp, G.C., Yanuka, M., Zebchuk, W.D., and Zegelin, S.J. (1988) Determination of electrical conductivity using time domain reflectometry: Soil and water experiments in coaxial lines. Water Resour. Res. 24(7):945-952.

Wraith, J.M., Comfort, S.D., Woodbury, B.L., and Inskeep, W.P. (1993) A simplified waveform analysis approach for monitoring solute transport using time-domain reflectometry. Soil Sci. Soc. Am. J. 57(3):637-642.

Table 1. NAND gate logic used to latch coaxial I/O location when address is good.

Jumper Select	SDE	Gate 2	Gate 1	Gate 4
H	H	L	L	H
H	L	L	H	L
L	H	H	L	H
L	L	H	L	H

Table 2. Current draw when switched to different input channels. Data from five multiplexers.

Current (mA)			
Channel	**Mean**	**Max.**	**Min.**
1	6.1	6.7	3.5
2	30.7	31.3	27.8
3	30.6	31.7	27.9
4	54.7	55.7	51.9
5	30.5	31.2	27.7
6	54.7	55.3	52.2
7	54.3	55.3	51.8
8	77.9	79.0	75.5
9	30.6	31.2	28.0
10	54.8	55.6	52.3
11	54.4	55.2	51.4
12	77.8	79.0	75.0
13	54.1	55.0	51.0
14	77.9	78.8	74.6
15	77.6	78.7	74.2
16	100.7	102.3	96.8

Table 3. Travel times, water contents (θ_v), and apparent dielectric constants (K_a) for a single 30 cm probe in sand saturated with distilled water with the wave form acquired on each channel of five different multiplexers; and, with the wave form acquired through channel one of a single multiplexer.

	t1.bis (ns)	t1 (ns)	t2 (ns)	tt (ns)	θ_v (m^3 m^{-3})	K_a
Five multiplexers, one reading on each channel of each for 80 readings total.						
Mean	1.619	2.096	10.780	8.684	0.331	18.83
SD	0.033	0.012	0.013	0.011	0.0006	0.047
Maximum	1.698	2.128	10.815	8.709	0.332	18.93
Minimum	1.545	2.068	10.751	8.663	0.329	18.73
First	1.630	2.095	10.784	8.689	0.331	18.85
Last	1.613	2.097	10.780	8.683	0.330	18.82
Multiplexer no. B2, 80 readings on channel 1.						
Mean	1.663	2.121	10.808	8.687	0.331	18.84
SD	0.028	0.006	0.005	0.007	0.0004	0.030
Maximum	1.702	2.136	10.821	8.707	0.332	18.92
Minimum	1.589	2.106	10.783	8.669	0.330	18.76
First	1.657	2.123	10.813	8.690	0.331	18.85
Last	1.663	2.123	10.807	8.685	0.331	18.83

Table 4. Wave form levels for a single 30 cm probe in sand saturated with distilled water with the wave form acquired on each channel of five different multiplexers; and, with the wave form acquired through channel one of a single multiplexer.

	V_i	V_r	V_0	V_{min}	V_f	$2V_0/V_f - 1$
Five multiplexers, one reading on each channel of each for 80 readings total.						
Mean	3715.7	5253.6	5295.0	5248.8	6512.2	0.1295
SD	0.27	0.23	0.75	1.04	0.24	0.0006
Maximum	3716.2	5254.1	5298.2	5252.3	6512.8	0.1318
Minimum	3715.0	5253.1	5294.0	5247.3	6511.6	0.1288
Multiplexer no. B2, 80 readings on channel 1.						
Mean	3715.4	5253.7	5295.1	5247.5	6512.3	0.1296
SD	0.19	0.22	0.27	0.88	0.15	0.0002
Maximum	3715.9	5254.2	5295.8	5249.4	6512.6	0.1301
Minimum	3714.9	5253.2	5294.5	5245.4	6511.8	0.1291

Table 5. Wave form levels and travel times, water content (θ_v), and apparent dielectric constant (K_a) for a single 20 cm probe in sand saturated with distilled water, 80 wave forms each.

WAVE FORM LEVELS						
	V_i	V_r	V_0	V_{min}	V_f	$2V_0/V_f - 1$
Two multiplexers, 6.92 m cable						
Mean	3712.6	5247.4	5275.8	5261.5	6572.7	0.0931
SD	0.20	0.20	0.18	0.37	0.16	0.0002
One multiplexer, 6.92 m cable						
Mean	3713.1	5247.2	5274.7	5258.5	6572.7	0.0921
SD	0.22	0.23	0.21	0.38	0.16	0.0001
No multiplexer, 6.92 m cable						
Mean	3713.0	5247.2	5273.1	5257.4	6572.4	0.0912
SD	0.19	0.24	0.24	0.40	0.16	0.0002

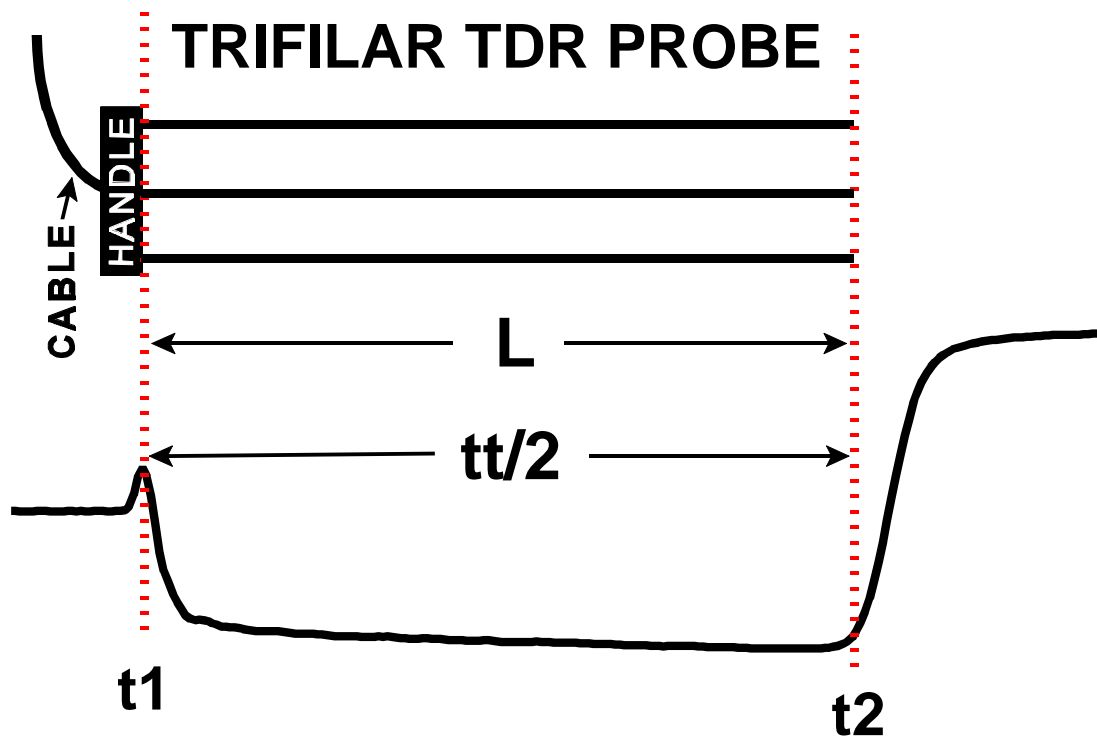| TRAVEL TIMES, WATER CONTENT, and K_a						
	t1.bis (ns)	t1 (ns)	t2 (ns)	tt (ns)	θ_v ($m^3\,m^{-3}$)	K_a
Two multiplexers, 6.92 m cable						
Mean	1.117	1.637	7.811	6.174	0.362	21.41
SD	0.005	0.005	0.002	0.005	0.0004	0.037
One multiplexer, 6.92 m cable						
Mean	1.069	1.589	7.720	6.131	0.359	21.12
SD	0.004	0.004	0.002	0.004	0.0003	0.030
No multiplexer, 6.92 m cable						
Mean	1.068	1.588	7.722	6.134	0.359	21.13
SD	0.003	0.003	0.002	0.004	0.0003	0.029

Figure 1. Relationship of trifilar TDR probe parts (top) to wave form features (bottom) for a prototypical wave form representing wet sand. For the wave form, the vertical dimension represents relative voltage and the horizontal dimension represents time. Thus t1 and t2 are times and the difference t1 - t2 is one half the two way travel time or tt/2 which corresponds to the exposed rod length, L. The vertical dotted lines indicate the correspondence between t1 and the point at which the rods exit the plastic handle; and, the correspondence between t2 and the ends of the probe rods.
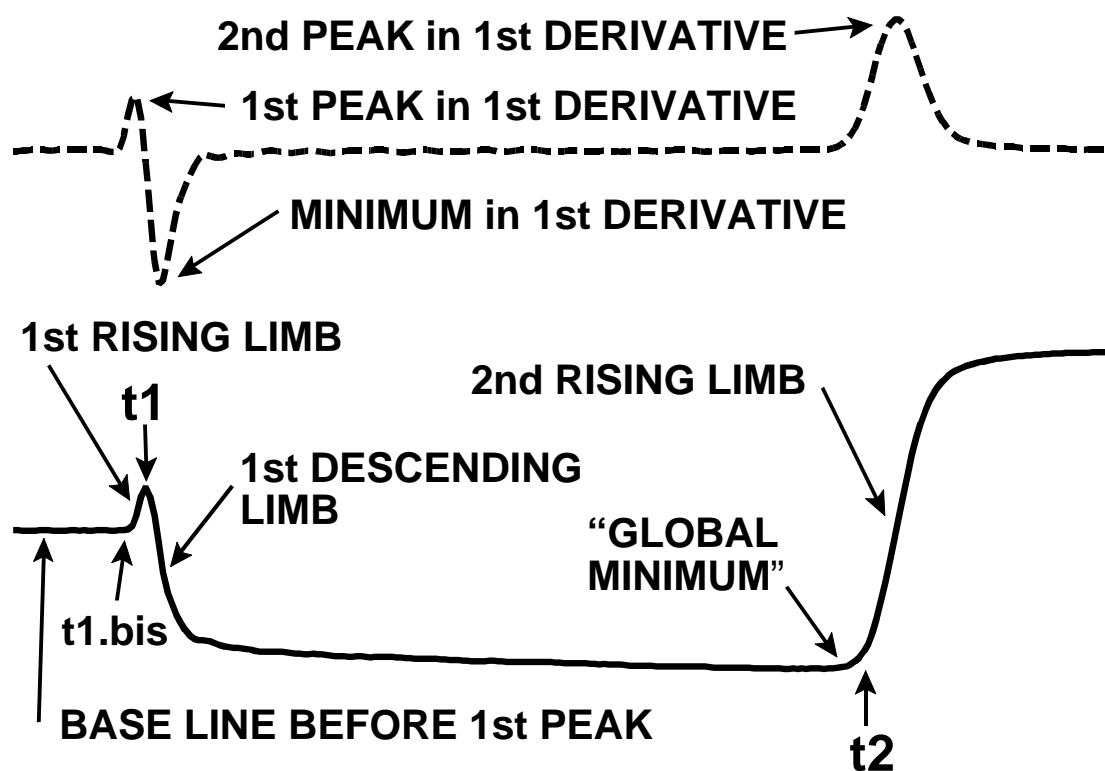
Figure 2. The TDR wave form (bottom) and the first derivative of the wave form with respect to time (top), with labels for features important for graphical interpretation.
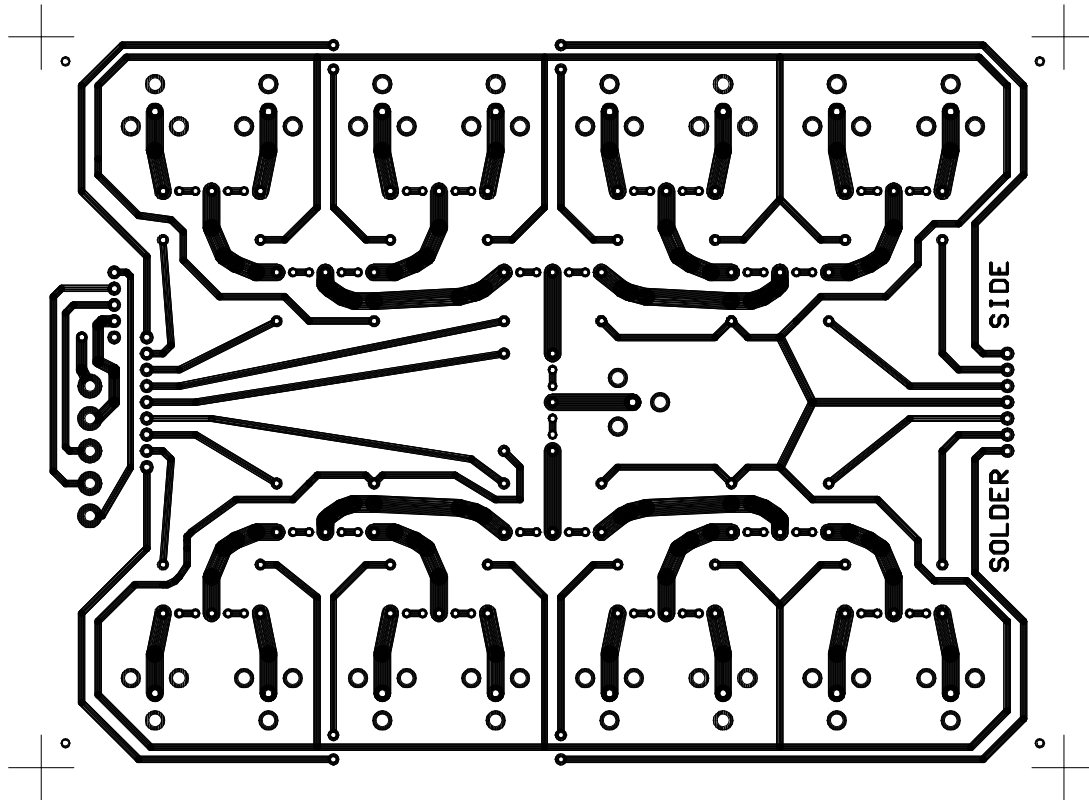
Figure 3. Solder side of relay board showing equal length tree structure of wave guide paths (wide traces), relay coil connections (narrow traces), and BNC connector locations (triangular pad patterns along top and bottom and near center). Also shown are single in-line header locations (one at right and two at left) and the position of the five pin power and control connector at far left. From the central BNC connector (triangular pad pattern just to right of center) the wave guide length is equal to any of the BNC connectors around the edges of the board.
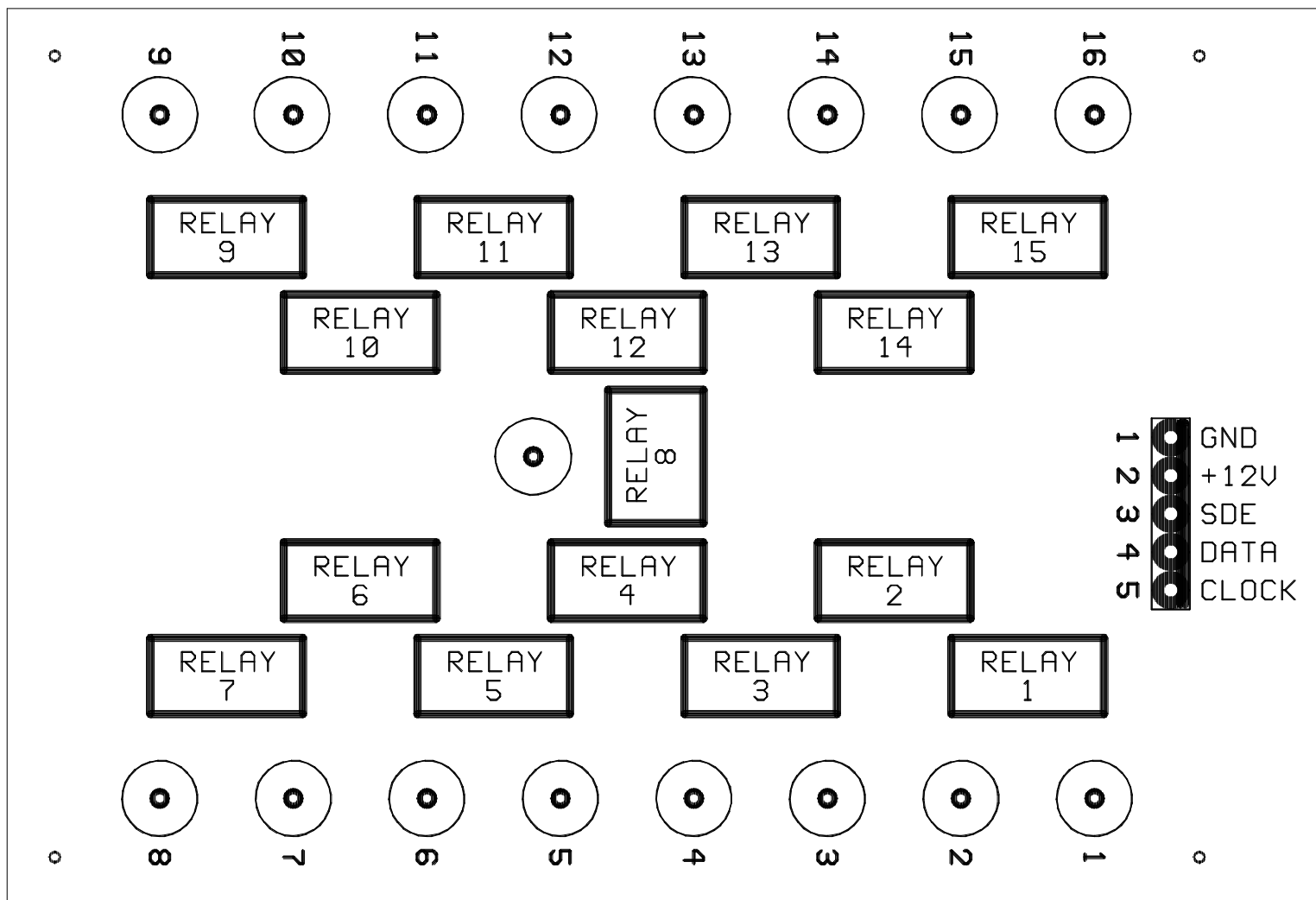
Figure 4. Top side of relay board showing relay positions, BNC connector positions (concentric circles), and the five pole, polarized connector for control and power wires.
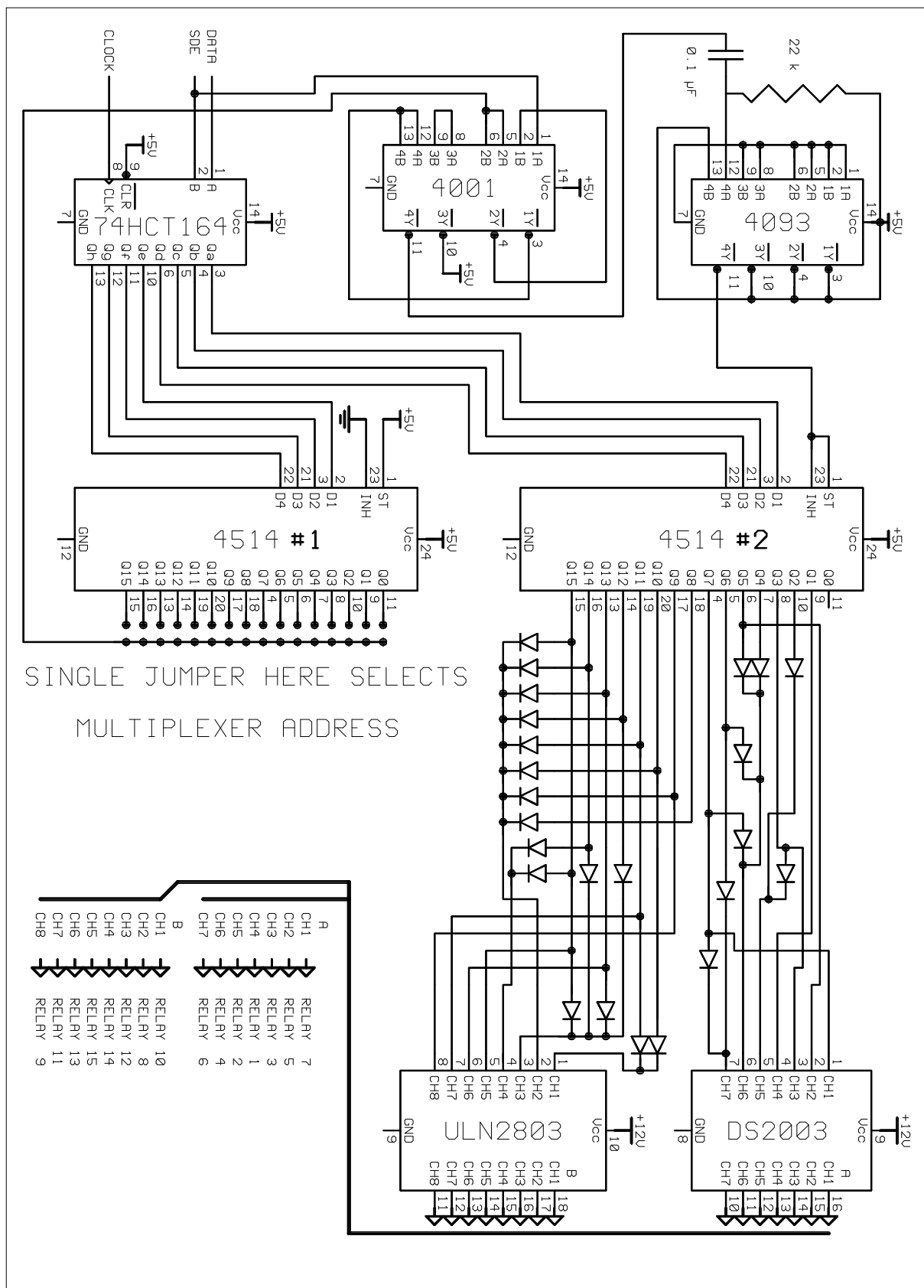
Figure 5. Schematic of control board circuitry.